ADVANCES IN COAL CLEANING

Ilham Demir, Latif A. Khan, and John M. Lytle
Illinois State Geological Survey, 615 E.Peabody Drive, Champaign, Illinois 61820

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INTRODUCTION

Run-of-mine coal generally has an ash content of 5-40% and a sulfur (S) content of 0.3-8% depending on the geologic conditions and mining technique used. Coal cleaning, therefore, is often required to remove excessive impurities for efficient and environmentally safe utilization of coal. In the US, the coal cleaning is most common at Eastern and Midwestern mines. Over 90% of the 267 US plants operated in 1998 were in eight Eastern and Midwestern states: West Virginia, 70; Kentucky, 56; Pennsylvania, 41; Virginia, 23; Indiana, 16; Illinois, 15; Ohio, 12; and Alabama, 11.[1]

Current commercial coal cleaning methods are invariably based on physical separation; chemical and biological methods tend to be too expensive. Typically, density separation is used to clean coarse coal while surface property-based methods are preferred for fine coal cleaning. In the density-based processes, coal particles are added to a liquid medium and then subjected to gravity or centrifugal forces to separate the organic-rich (float) phase from the mineral-rich (sink) phase. Density-based separation is the most common coal cleaning method and is commercially accomplished by the use of jigs, mineral spirals, concentrating tables, hydrocyclones, and heavy media separators. The performance of density-based cleaning circuits is estimated by using laboratory float-sink (F-S) tests. In the surface property-based processes, ground coal is mixed with water and a small amount of collector reagent is added to increase the hydrophobicity of coal surfaces. Subsequently, air bubbles are introduced in the presence of a frother to carry the coal particles to the top of the slurry, separating them from the hydrophilic mineral particles. Commercial surface property-based cleaning is accomplished through froth or column flotation. To estimate the performance of flotation devices, a laboratory test called release analysis is used.[2-5]

Theoretically, the efficiency of physical cleaning should increase as particle size decreases because of the improved liberation of the mineral matter from the coal matrix. Therefore, recent research on advanced coal cleaning has focused on improving fine-coal cleaning. Column flotation devices developed since the 1980s can remove most of the impurities from finely-ground coal.[6-8] Likewise, advanced gravity separators, developed mainly for metal mining industries, were shown in recent years to have a good potential for improving the cleaning of finely-ground coal.[9,10] This paper discusses work on physical fine-coal cleaning conducted at the Illinois State Geological Survey (ISGS) and reviews work conducted elsewhere on the similar subject.

LABORATORY TESTS TO ASSESS FURTHER CLEANABILITY OF ILLINOIS COALS

As-shipped (cleaned) coals from eight coal preparation plants in Illinois were selected to assess the further cleanability of conventionally cleaned coals.[11] The criteria for sample selection were based on the representation of the main producing seams, high and low S coals, high and low ash coals, and different geographic regions of the Illinois coal field. Therefore, the interpretations reported here should apply to most marketed coals from Illinois mines. Release analysis (RA) and F-S test data were generated to estimate the beneficiation of the eight coals, at -60 mesh (<250 μm) particle size and 80%-combustibles recovery.

Froth Floatation Cleanability The RA tests indicated that ash yield and S content of Illinois coals could be reduced substantially beyond conventional cleaning through the use of froth flotation or column flotation. The ash yield was reduced by 24-69% and S content by 4-24% relative to the parent coals (Table 1). The proportion of the total S removed increased with increasing ratio of pyritic to organic S.[11] Both the absolute and relative reduction of ash yield tended to increase with the amount of ash yield in the parent coal.

The RA separation resulted also in significant reductions for the contents of most elements that are classified as hazardous air pollutants or HAPs (Table 1). In some cases, reductions for HAPs approached or exceeded the reductions for ash. Reductions for Mn and P approached or exceeded reductions for ash in almost all cases. A substantial portion of Mn is thought to occur in solid solution in calcite, and P is associated, perhaps primarily, with apatite in coal. Most of the calcite and some of the apatite occur as cleat fillings, nodules, and/or partings[12,13] which are more easily removed during coal cleaning than finely disseminated minerals.

Float-Sink Washability The F-S washability data indicated that density (gravity)-based physical fine-coal cleaning can be quite effective in further reducing ash and S contents of marketed Illinois coals (Table 1). Clean coals having ash yields of 3.6-6.8% can be produced from the eight coals. The ash yields were reduced by 47-75% relative to conventional cleaning. The S content of the eight clean F-S products varied between 0.73% and 3.28%, representing a 21-42% reduction. Comparison of the S data from this study with the data on S forms of feed coals[14] indicated that the S remaining in the clean F-S products is overwhelmingly organic S; most of the inorganic S was removed during the F-S process.

The clean F-S products had much smaller HAP contents than the conventionally cleaned feed coals, with a few exceptions (Table 1). Reductions of As, Cd, Hg, Mn, and P contents exceeded reductions for ash in almost all cases. Arsenic, Cd, and Hg are associated mostly with sulfide minerals[15] that have high specific gravities and, therefore, respond to gravity separation efficiently. Minerals containing substantial amounts of Mn (calcite) and P (apatite) also showed efficient response to the F-S separation, as well as RA, because, as indicated earlier, these minerals tend to occur as relatively coarse grains in cleat fillings, nodules, or partings. Because As, Cd, F, Hg, Pb, and Se have relatively high atmospheric mobilities during coal combustion[15,16], achieving high removal values for these elements is important from an environmental point of view. Those HAPs that were reduced less than the ash apparently occurred either in organic form or in extremely fine mineral particles disseminated in the organic matter which were not liberated by grinding the coals to the selected particle size. This may be the case for Be, Sb and U in some of the samples. However, the elements that exhibited enrichment or relatively low cleanabilities either have low concentrations in Illinois coals or low atmospheric mobilities during coal combustion[15,16] which would result in low environmental risk associated with their emissions.

In general, the beneficiation of the eight coals through the use of the F-S test was considerably greater than the beneficiation obtained through the RA test (Figure 1). The difference between the F-S and RA results was particularly large for some samples (Table 1). The effectiveness of the F-S separation for the most environmentally critical elements, S and Hg, is particularly important. Because Be tended to stay largely with the organic matter, it was generally enriched more in the F-S products than in the RA products. The comparison of the F-S and RA data suggested that RA can estimate the performance of standard flotation circuits but probably not the performance of advanced gravity separators and some advanced flotation devices. Float-sink tests appear to be more suitable to estimate the ultimate cleanability of coal through the use of advanced physical cleaning.

PILOT SCALE TESTS WITH ISGS FROTH WASHER DEVICE

A froth washer device was developed at the ISGS to improve the performance of both subaeration cells and flotation columns.[17] The ISGS froth washer enables the washing and quick removal of fine contaminants into a separate stream of a flotation circuit. Tests conducted on IBC-112 coal in the Illinois Basin Coal Sample Program indicated that a subaeration cell equipped with the ISGS froth washer removed more ash-forming minerals and S from the coal than a packed column device (Figure 2). The performance of the modified subaeration cell generally approached the ultimate cleanability predicted from F-S tests and the so-called advanced flotation washability analysis (AFW) as defined elsewhere.[17] Using the subaeration cell with the ISGS washer, a second set of tests was performed on a sample of preparation plant fines containing 43.5% ash, 4.2% total S, 2.0% pyritic S, and having a heating value of 7934 Btu/lb. The optimized performance of the subaeration cell with the ISGS washer at a throughput of 50 lb/hr/ft^3 approached that of the AFW process, resulting in 75% ash rejection and 45% pyritic S rejection at 83%-combustibles recovery.

PILOT AND FULL-SCALE TESTS WITH ENHANCED GRAVITY SEPARATORS

It has been reported that gravity-based separation can potentially be superior to surface property-based separation for reducing the pyrite content of coal.[15] Honaker and co-workers[9,10,19-21] evaluated the application of enhanced gravity separation to pilot and full-scale coal cleaning. Using a dense medium Falcon gravity separator, the ash yield and pyritic S content of a 28x325 mesh coal collected from a preparation plant treating Illinois Herrin (No. 6) Coal were reduced from 17.5% to 3.5% and from 0.55% to 0.15%, respectively, while recovering 87.8% of the combustible material.[19] Comparison with AFW data suggested that the dense medium Falcon Concentrator can potentially outperform the best flotation technology available. Pilot scale tests with a Falcon Concentrator, a Knelson Concentrator, and an Altair Jig indicated that they were all effective for cleaning a 28x400 mesh coal sample from the Illinois Springfield (No. 5) Coal.[20] Typically, 80% of the ash and 70% of the total S were rejected at 85% recovery of the combustible material. During full-scale testing with a mass flow rate of 100 t/hr, the Falcon Concentrator efficiently cleaned a refuse pond coal sample.[20] The ash yield was reduced from 22% to 8% for the 28x100 mesh fraction and from 32% to 15 % for the 100x500 mesh fraction, while recovering a little over 80% of the combustible material. Nearly 90% of the pyritic S was rejected, resulting in the reduction of the total S content of both fractions from 7.9% to 2.7% .

OTHER PHYSICAL METHODS FOR ADVANCED COAL CLEANING

Other physical cleaning methods, including selective agglomeration, heavy medium cycloning, and dry separation with electrical and magnetic methods, have been discussed by Couch.[22,23] Selective agglomeration and advanced cycloning have the high probability of commercialization, particularly for reducing S content of coal.[23] In selective agglomeration, the coal is mixed with oil. The oil wets the surface of coal particles and thus causes them to stick together to form agglomerates. The agglomerated coal particles are then separated from the mineral particles that stay in suspension because they do not attract oil to their surfaces. A version of selective agglomeration, called the Otisca T-process, was reported to reduce the ash content of some coals, ground to about 2 μm, below 1% with a high recovery of the heat content.[24] Conventional cycloning has been used for many years for cleaning relatively coarse coal and considered for fine coal cleaning only in recent years. Coal and heavy medium enters the conical-shape cyclone tangentially near the top. As the cyclone spins around its axis, impurities move downward along the walls and exit through the bottom opening while coal particles move upward near the center and exit from the top. Dry methods that take advantage of the differences between electrical or magnetic properties of minerals and coal particles have not developed enough for commercial applications.

COST OF ADVANCED COAL CLEANING

Progress in fine-coal cleaning has been significant, but the dewatering and material handling stages of the process can be difficult and are expensive. Therefore, the economic and environmental benefits of the final product must justify the cost. Newman et al.[25] estimated the cost of advanced cleaning to be $12/t for run-of-mine coals containing 1-8% S if 90% pyritic S rejection is to be achieved. It is not clear whether dewatering and fine-particle handling costs were included in these estimates. The total cost of advanced cleaning, including dewatering and pelletization (or briquetting), might be $22-27.5/t.[26] One should, however, keep in mind that the product of advanced coal cleaning is a low-ash, low-S, and high-heating value fuel. Therefore, some expenses of the advanced coal cleaning can be offset by (1) reduction in transportation cost per unit of heating value of coal, (2) elimination of milling cost at power plants, and (3) reduced maintenance cost of power plants related to fouling, slagging, and other wear and tear. Furthermore, the pelletization or briquetting costs may be eliminated if the advanced cleaning product is used as a coal-water fuel to replace oil in oil-fired boilers. Transporting coal-water fuels through pipelines would provide further cost-cutting benefits. Although the application of advanced fine-coal cleaning is currently limited, its widespread commercialization may eventually take place, depending on further improvements in technology, supply and demand for different fuels, and future environmental regulations.

CONCLUSIONS

Release analysis (RA) and float-sink (F-S) test data for selected samples suggested that advanced physical cleaning at -60 mesh particle size and 80%-combustibles recovery can potentially reduce the ash yield and S content of Illinois coals up to 75% and 42%, respectively, beyond conventional cleaning. As a result, some of the clean products would have ash yields of <4% and S content of <1%. The F-S process was generally more effective than the RA process for cleaning the samples. The average F-S reductions for HAPs were (in %): As(67), Cd(78), Hg(73) Mn(71), P(66), Co(31), Cr(27), F(39), Ni(25), Pb(50), Sb(20), Se(39), Th(32), and U(8). Beryllium was generally enriched in the clean RA and F-S products. However, elements with relatively low removal or enrichment values would have very little, if any, environmental impact because they either occur in very small quantities in Illinois coals or are fixed largely in coarse ash and slag during coal combustion.

Two advanced cleaning technologies tested on Illinois coals in recent years yielded promising results. The performance of a froth washer device developed at the ISGS to improve the performance of both subaeration cells and flotation columns generally approached the ultimate cleanability predicted from laboratory F-S tests. Pilot and full-scale tests with advanced gravity separators, performed at Southern Illinois University, suggested that such equipment can potentially outperform even the best flotation technology available.

The estimated cost of advanced fine-coal cleaning ranges from $12 to $28 per ton, which is uneconomical under current conditions. However, some expenses of advanced coal cleaning can be offset by reduction in transportation cost, elimination of milling cost at power plants, and reduced maintenance cost of power plants. Widespread commercialization of advanced coal cleaning technologies depends on further improvements in technology, supply and demand for different fuels, and future environmental regulations.

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Table 1. Analyses of the eight as-shipped Illinois coals and their clean RA and F-S products at -60 mesh size and 80%-combustibles recovery. All values are on a dry basis.

Feed Lab no.	Feed or Cleaning product	Heating value (Btu/lb))	Ash yield (%)	S (%)	HAP elements (mg/kg) As	Be	Cd	Co	Cr	F	Hg	Mn	Ni	P	Pb	Sb	Se	Th	U
C32778	feed	12709	9.80	1.60	10	2.2	0.60	4.6	12	70	0.04	38	31	87	14	2.2	1.5	1.5	0.9
	RA product	13622	5.63	1.21	5.8	2.6	<0.2	4.0	9.7	57	0.05	13	29	39	8	2.2	1.0	1.3	1.1
	F-S product	13962	4.79	1.19	2.9	4.6	<0.08	3.8	9.4	59	0.01	12	29	39	7	2.2	1.0	1.2	1.3
C32782	feed	12503	11.62	3.90	2.4	<1.0	0.40	1.6	14	78	0.07	55	7	87	<6	0.5	1.9	1.1	1.3
	RA product	13448	8.97	3.65	1.3	1.3	<0.2	1.2	10	66	0.04	18	6	31	4	0.4	1.3	0.9	1.4
	F-S product	13797	5.89	2.99	0.9	2.2	<0.1	1.2	9.7	63	0.02	15	5	28	3	0.4	1.0	0.9	1.4
C32785	feed	12741	9.75	4.17	2.3	1.5	0.40	2.6	17	115	0.07	39	18	131	<5	0.4	3.9	1.3	1.8
	RA product	13538	6.54	4.00	1.6	2.0	<0.3	2.0	12	89	0.07	17	16	35	7	0.4	2.8	1.1	1.8
	F-S product	14029	4.38	3.28	0.7	1.5	0.10	1.8	12	87	0.01	12	14	31	3	0.2	1.9	1.0	1.4
C32815	feed	12422	12.03	3.73	3.0	<1.0	<0.2	2.7	14	88	0.06	61	10	44	12	0.6	2.1	1.7	1.9
	RA product	13538	8.72	3.23	1.8	1.4	<0.3	2.1	13	80	0.05	19	8	17	7	0.5	1.8	1.4	1.9
	F-S product	13933	5.01	2.80	0.9	2.1	<0.09	1.7	11	69	0.02	18	7	13	7	0.4	1.0	1.2	1.9
C32796	feed	12120	16.10	1.05	9.8	1.0	0.90	8.5	19	123	0.06	41	24	87	31	1.0	2.0	3.0	1.0
	RA product	12908	10.59	0.82	8.7	1.9	<0.4	6.5	17	95	0.06	17	19	44	27	0.9	1.9	2.4	0.7
	F-S product	14277	6.80	0.73	4.2	1.7	0.04	5.5	14	51	0.02	11	19	32	14	1.0	1.3	1.6	0.7
C32662	feed	13525	7.00	1.51	14	1.4	<0.3	4.4	10	83	0.08	15	17	175	23	1.0	1.3	1.9	1.9
	RA product	13892	4.58	1.33	9.4	1.9	<0.2	2.8	8.8	65	0.08	8.6	15	100	17	0.9	1.1	1.5	1.6
	F-S product	14143	3.67	1.11	5.2	2.7	<0.07	2.6	7.8	43	0.02	6.0	12	74	14	0.8	0.9	1.2	1.6
C32781	feed	13773	9.71	3.02	4.3	<1.0	0.50	2.7	12	104	0.11	37	11	44	46	1.4	2.5	1.2	2.0
	RA product	13456	7.41	2.86	2.8	1.1	<0.3	1.6	11	63	0.10	18	11	26	28	1.0	1.6	1.1	1.6
	FS product	13915	5.19	2.04	1.4	1.1	<0.09	1.7	9.9	67	0.04	10	8	13	19	1.0	1.3	0.9	1.5
C32793	feed	12402	14.14	1.64	33	1.2	<0.2	5.5	13	124	0.13	39	22	175	36	1.2	1.1	1.8	0.8
	RA product	13947	4.35	1.28	16	1.2	<0.2	4.4	6.0	71	0.09	7.5	16	96	28	1.2	1.0	1.0	0.5
	F-S product	14151	3.59	0.95	6.4	2.0	<0.06	3.7	7.0	38	0.03	8.0	15	57	14	1.1	0.9	0.8	0.8
RA mean %change*		7	-40	-14	-39	32	-26	-25	-19	-26	-9	-63	-13	-54	-24	-11	-21	-20	-9
RA min. %change**		2	-24	-4	-30	0	0	-13	-7	-9	0	-51	0	-41	-13	0	-5	-8	0
RA max.%change**		12	-69	-24	-46	90	-67	-36	-38	-43	-43	-81	-21	-73	-43	-29	-33	-44	-36
F-S mean %change*		10	-55	-28	-67	74	-77	-31	-27	-39	-73	-71	-25	-66	-50	-20	-39	-32	-8
F-S min. %change**		1	-47	-21	-57	0	-55	-17	-18	-16	-64	-60	-6	-55	-39	0	-16	-16	0
F-S max. %change**		16	-75	-42	-75	120	-96	-37	-46	-69	-66	-79	-32	-76	-61	-50	-52	-56	44

* Mean percentage decrease (negative values) or increase (positive values) in heating value, ash yield, or elemental concentrations for the eight coals. %change for each coal = ((Feed value - Product value)/(Feed value))x100. For values below detection limits, the upper limits were used in the computations.

**Absolute change, regardless of sign.

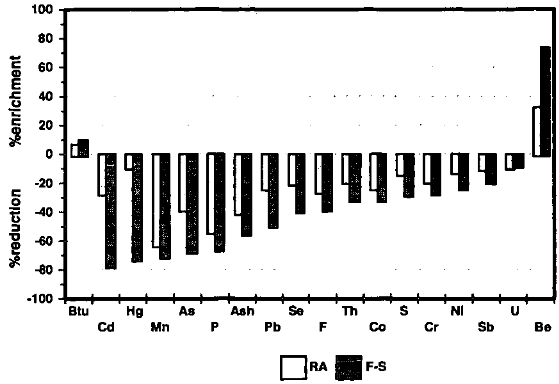
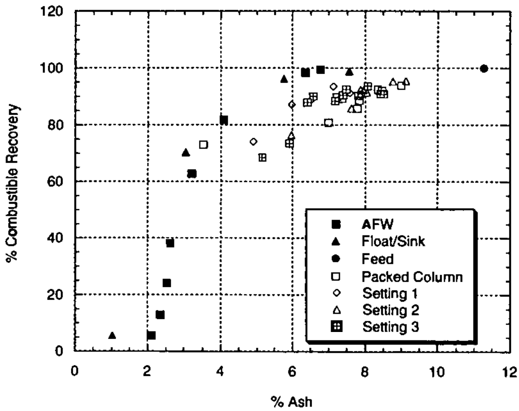


Figure 1. Average changes in heat content (Btu), ash yield, and concentrations of S and HAPs of the eight selected samples of as-shipped Illinois coals as a result of release analysis (RA) and float-sink (F-S) separations at -60 mesh particle size and 80%-combustibles recovery.



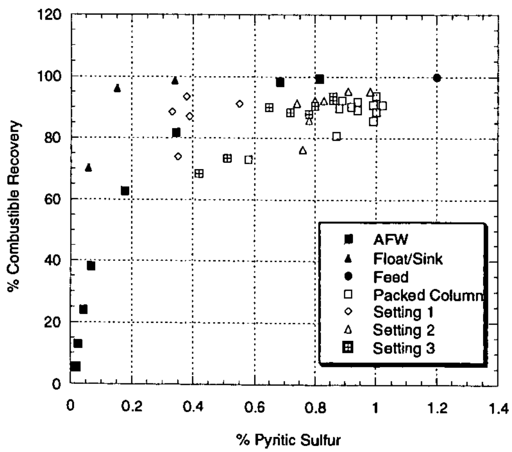


Figure 2. Ash and pyritic S vs. combustible recovery for cleaning IBC-112 ground to 90% -200 mesh using a subaeration cell with the ISGS washer at various settings. For each test, 2 lb/ton kerosene and 2 lb/ton M650 were used.